New Results in Neutrino Measurements

William C. Louis

Physics Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract. The field of Neutrino Physics has been spectacularly successful in recent years with the discovery of neutrino oscillations and neutrino mass. Nevertheless, neutrino properties are still largely unknown with many fundamental questions yet to be answered. Many of these questions will be answered by future neutrino experiments, including the ongoing MiniBooNE and MINOS experiments at Fermilab, which will make definitive tests of the LSND neutrino oscillation result and measurements of atmospheric neutrino oscillations, respectively.

NEUTRINO PAST

Neutrino oscillation experiments have made a profound contribution to nuclear and particle physics with the discovery of neutrino oscillations and neutrino mass. Solar neutrino experiments, including Homestake, Kamiokande, SAGE, GALLEX, GNO, SuperKamiokande, SNO, and KamLAND, have observed neutrino oscillations at $\Delta m^2 \sim 8 \times 10^{-5}$ eV^2, while atmospheric neutrino experiments, including IMB, Kamiokande, SOUDAN, SuperKamiokande, MACRO, and K2K, have observed neutrino oscillations at a mass scale of $\Delta m^2 \sim 2 \times 10^{-3}$ eV^2. In addition to these observations of neutrino oscillations, the LSND experiment [1] has evidence for neutrino oscillations at a large mass scale of $\Delta m^2 \sim 1$ eV^2. If these oscillation regions, shown in Fig. 1, are all correct, then there is a problem (a "$3 - \Delta m^2$" paradox) because it is not possible to explain all three disparate mass scales with only three neutrinos. Therefore, if the LSND oscillation signal is confirmed, then LSND together with the solar and atmospheric neutrino oscillation experiments will imply physics Beyond the Standard Model. Possible physics Beyond the Standard Model models that would explain the data appear to all employ sterile neutrinos (i.e. neutrinos that do not participate in the Standard Model weak interaction), which would have a big effect on astrophysics and cosmology as well as nuclear and particle physics. These models include a "3+2" model with two sterile neutrinos [2] or various "3+1" models with other new physics, such as mass-varying neutrinos [3], CPT violation [4], quantum decoherence [5], Lorentz violation [6], extra dimensions [7], and sterile neutrino decay [8]. Needless to say, these models are probably not all correct; however, if even just one model is correct, then it will be a major breakthrough.

NEUTRINO FUTURE

Despite the tremendous progress that has been made in neutrino physics over the last several years, neutrino properties are still largely unknown and there are many funda-
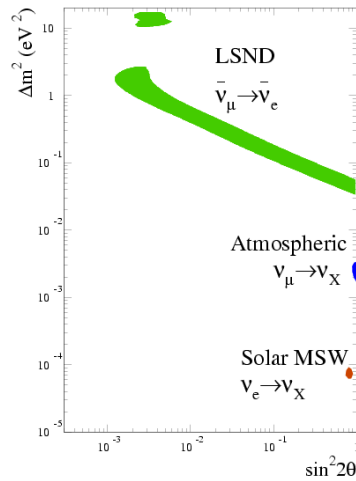
FIGURE 1. The allowed neutrino oscillation regions from solar neutrino oscillation experiments, atmospheric neutrino oscillation experiments, and from the LSND oscillation experiment.

mental questions that need to be answered. A partial list of questions includes:

- What are the absolute neutrino masses and hierarchy?
- What are all of the neutrino mixings?
- Are neutrinos Dirac or Majorana type?
- Is CP conserved in the lepton sector?
- Is CPT conserved in the lepton sector?
- Do light, sterile neutrinos exist?
- What is the resolution of the "$3 - \Delta m^2$" paradox?

In order to provide answers to many (if not all) of these questions, an exciting future neutrino physics program is being planned [9] for a diverse set of experiments, including tritium β decay, neutrinoless double β decay, reactor θ_{13}, accelerator θ_{13}, solar neutrino, atmospheric neutrino, large Δm^2, and neutrino cross sections. These future experiments have the capability of transforming our understanding of neutrinos and their role in nuclear physics, particle physics, and astrophysics.

NEUTRINO PRESENT

New results in neutrino measurements are presently being reported by the MINOS and MiniBooNE experiments at Fermilab and by the K2K experiment at KEK. MINOS is designed to make a definitive measurement of atmospheric neutrino oscillations, while MiniBooNE is designed to make a definitive test of the LSND neutrino oscillation evidence. K2K has already confirmed atmospheric neutrino oscillations [10] and is now presenting interesting results on neutrino cross sections. [11]

FIGURE 2. A schematic diagram of the MINOS neutrino baseline.

MINOS

The MINOS experiment is designed to measure ν_μ disappearance in the atmospheric neutrino oscillation region and to search for $\nu_\mu \to \nu_e$ appearance and oscillations to sterile neutrinos. In addition, due to the magnetized steel and underground location of the detector, MINOS is making the first separate measurement of neutrino oscillations for atmospheric ν_μ and $\bar{\nu}_\mu$. As shown in Fig. 2, the NuMI beamline produces neutrinos at Fermilab and sends them to the MINOS far detector, located at a distance of 735 km in the Soudan mine of northern Minnesota.

The NuMI neutrino beamline is fed by 120-GeV protons from the Fermilab Main Injector. Pions and kaons, which are produced by protons interacting on a graphite target, are focussed by 2 magnetic horns located downstream of the target, and then decay in a 675 m decay pipe. Downstream of the decay pipe are an absorber and three layers of muon monitors for measuring the muons from pion and kaon decay. The neutrino energy can be adjusted by varying target and horn distances.

There are two MINOS detectors located at 1 km and 735 km from the neutrino source. The near detector, located on site at Fermilab, consists of 292 planes of magnetized steel ($B = 1.2T$) and plastic scintillator and has a total mass of 0.98 ktons. The far detector, located in the Soudan mine, consists of 486 planes of magnetized steel ($B = 1.3T$) and plastic scintillator and has a total mass of 5.4 ktons.

Figs. 3 and 4 show the MINOS sensitivities for ν_μ disappearance and ν_e appearance, respectively. If neutrino oscillations occur, for example, at $\Delta m^2 = 0.0025$ eV^2 and $\sin^2 2\theta = 1.0$, then MINOS will observe a clear distortion of the neutrino energy distribution and will be able to make a precision measurement of the ν_μ disappearance oscillation parameters. In addition, MINOS will be able to improve the ν_e appearance sensitivity by a factor of ~ 2 over the CHOOZ sensitivity and will have the capability of measuring a non-zero value for θ_{13}.

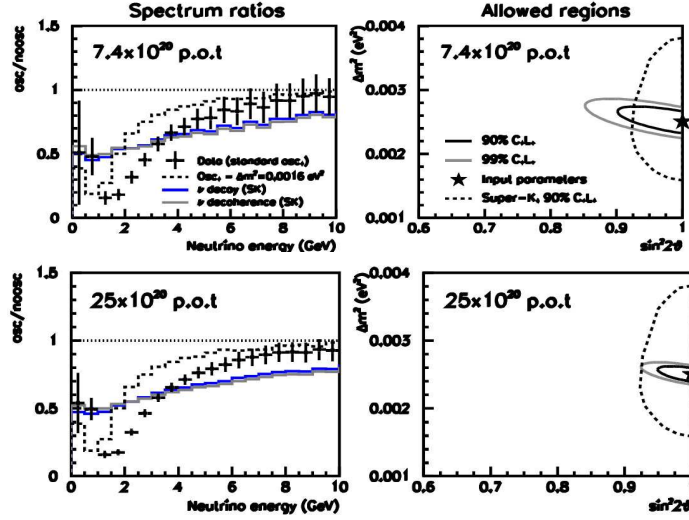Due to the magnetized steel and underground location of the far detector, MINOS is

FIGURE 3. If neutrino oscillations occur, for example, at $\Delta m^2 = 0.0025$ eV^2 and $\sin^2 2\theta = 1.0$, then MINOS will observe a clear distortion of the neutrino energy distribution and will be able to make a precision measurement of the ν_μ disappearance oscillation parameters.
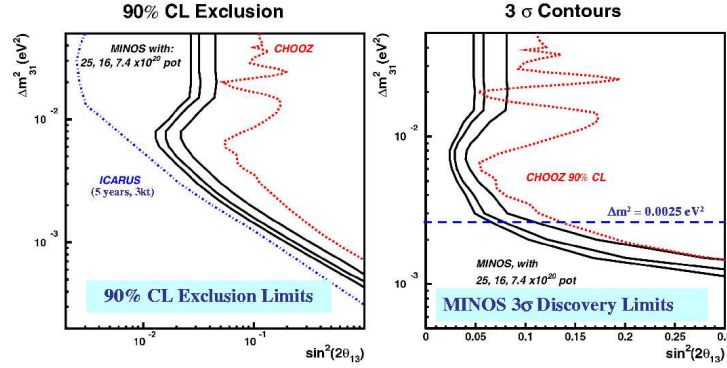

FIGURE 4. The MINOS sensitivity for ν_μ disappearance and ν_e appearance.

making the first separate measurement of atmospheric neutrinos and antineutrinos. Fig. 5 shows the L/E_ν distribution for fully-contained and partially-contained atmospheric neutrino events in the MINOS far detector. The data already favor the expectation from neutrino oscillations compared to the no-oscillation case. Also, Fig. 6 shows the charge-separated up/down distributions for atmospheric neutrinos and antineutrinos. The data are consistent with ν_μ and $\bar{\nu}_\mu$ oscillating with the same parameters, although CPT violating scenarios [4] with large Δm_{23}^2 are not excluded by current data.

The MINOS detectors and NuMI beam construction and commisioning have been successfully completed and the experiment is operating well. This has allowed the experiment to collect atmospheric neutrino data since July 2003 and accelerator neutrino data since March 2005. A preprint on the first results from fully-contained and partially-
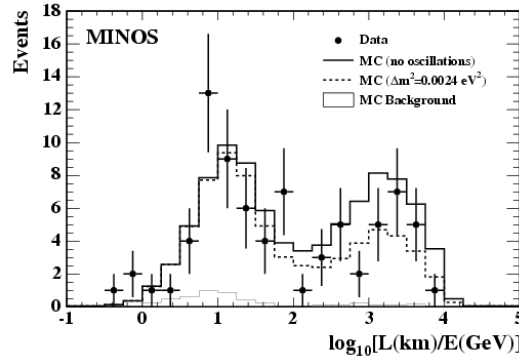
FIGURE 5. The L/E_ν distribution for fully-contained and partially-contained atmospheric neutrino events in the MINOS far detector.
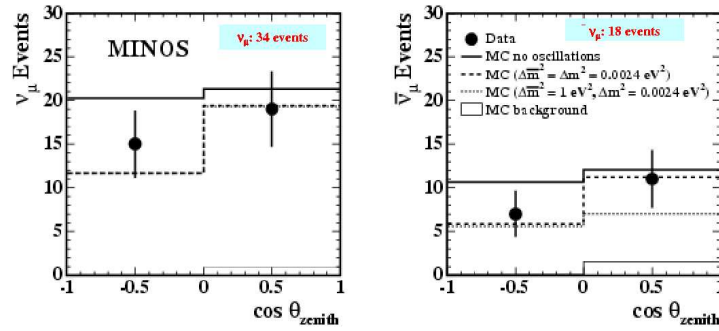

FIGURE 6. The MINOS charge-separated up/down distributions for atmospheric neutrinos and antineutrinos.

contained atmospheric neutrino events will be available soon. With the NuMI beam intensity continuously improving, 10^{20} protons on target are expected by the end of 2005, and first physics results from NuMI beam neutrinos are expected in 2006.

MiniBooNE

The MiniBooNE experiment is designed to search for $\nu_\mu \to \nu_e$ oscillations and will be a definitive test of the LSND oscillation signal. The experiment is located at Fermilab and has a neutrino baseline of ~ 0.5 km.

A schematic drawing of the MiniBooNE experiment is shown in Fig. 7. Protons from the 8-GeV Booster interact in a Be target that is located at the upstream end of a 170-kA magnetic-focusing horn. Secondary pions and kaons are focussed by the horn and then decay in a 50-m decay pipe into neutrinos with an average energy of ~ 1 GeV and with an intrinsic ν_e component of about 0.5%. The detector, located 541 m from the neutrino source, consists of a 40-foot diameter spherical tank that is covered on the inside by 1520 8-inch phototubes (1280 detector phototubes and 240 veto phototubes) and filled
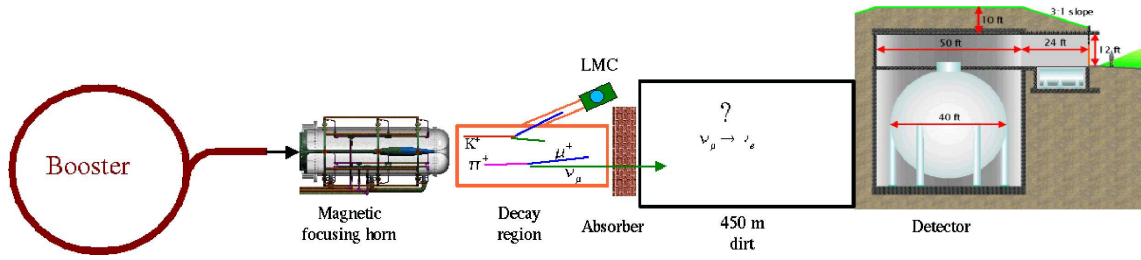
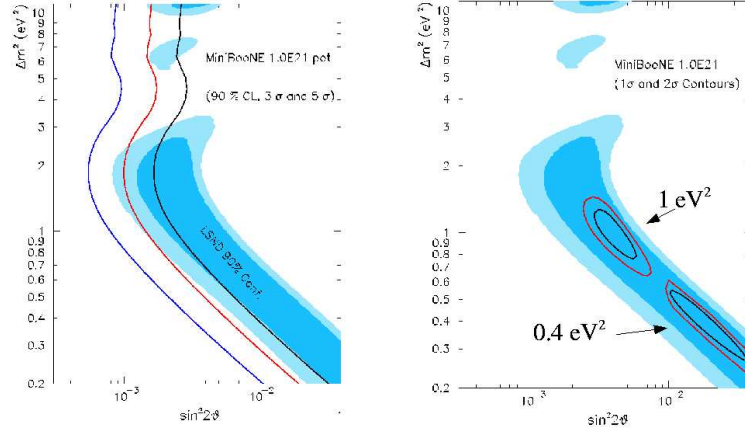**FIGURE 7.**   A schematic drawing of the MiniBooNE experiment.

FIGURE 8.   The expected MiniBooNE $\nu_\mu \rightarrow \nu_e$ oscillation sensitivity for 10^{21} protons on target and the expected allowed regions if neutrino oscillations occur at Δm^2 values of 1.0 eV^2 or 0.4 eV^2.

with ~ 800 tons of mineral oil.

The MiniBooNE neutrino flux is determined by fitting p-Be pion and kaon production data, including data from the recent E910 experiment at BNL [12] and the HARP experiment at CERN, [13] to a Sanford-Wang parameterization. The neutrino cross sections are determined using a modified version of the NUANCE cross section package. [14] Fig. 8 shows the expected MiniBooNE $\nu_\mu \rightarrow \nu_e$ oscillation sensitivity for 10^{21} protons on target and the expected allowed regions if neutrino oscillations occur at Δm^2 values of 1.0 eV^2 or 0.4 eV^2. MiniBooNE should be able to cover most of the LSND allowed region at the 5-sigma level.

About 48% of the MiniBooNE events are charged-current quasi-elastic (CCQE) events, $\nu_\mu\ {}^{12}C \rightarrow \mu^- p\ {}^{11}C^*$, and MiniBooNE now has one of the world's largest samples of these events. This CCQE sample is very important for measuring other neutrino cross sections, which are used as inputs to the ν_e appearance oscillation analysis. Fig. 9 shows the reconstructed E_ν and $\cos\theta$ distributions for CCQE events, where E_ν is the incident neutrino energy and θ is the angle of the outgoing muon relative to the incident neutrino direction. This CCQE sample is selected by requiring a single ring event that is consistent with a muon. The points with error bars are the data, while the error band corresponds to the Monte Carlo predicted shape with systematic uncertainties from neutrino cross sections and light scattering and extinction in the detector oil. There is fairly
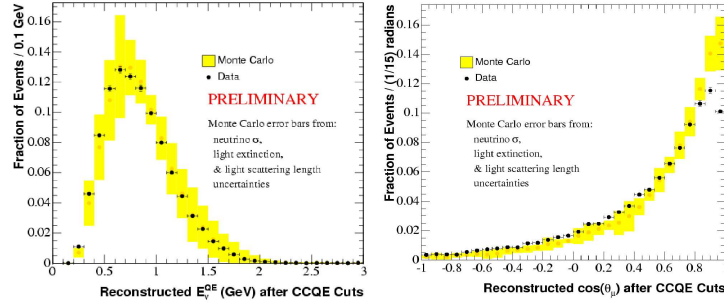
FIGURE 9. The MiniBooNE reconstructed E_ν and $\cos\theta$ distributions for CCQE events, where E_ν is the incident neutrino energy and θ is the angle of the outgoing muon relative to the incident neutrino direction. The points with error bars are the data, while the error band corresponds to the Monte Carlo predicted shape with systematic uncertainties.

FIGURE 10. The MiniBooNE reconstructed E_ν and $\cos\theta$ distributions for CCpi+ events, where E_ν is the incident neutrino energy and θ is the angle of the outgoing muon relative to the incident neutrino direction. The points with error bars are the data, while the error band corresponds to the Monte Carlo predicted shape with systematic uncertainties.
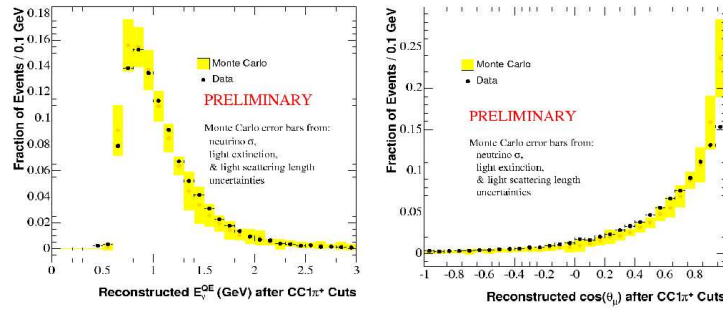
good agreement between the data and Monte Carlo, except in the region near $\cos\theta = 1$, where the data is suppressed relative to the Monte Carlo prediction. This suppression remains, at present, an interesting mystery.

About 31% of the MiniBooNE events are charged-current single-π^+ (CCpi+) events, $\nu_\mu \ {}^{12}C \rightarrow \mu^- \pi^+ X$. CCpi+ events are not well measured at low energies; however, MiniBooNE now has the world's largest sample of such events, where the selection is an event with 2 Michel-electrons from μ^- and μ^+ decay (from the decay of the π^+). Fig. 10 shows the reconstructed E_ν and $\cos\theta$ distributions for CCpi+ events, where E_ν is the incident neutrino energy and θ is the angle of the outgoing muon relative to the incident neutrino direction. The points with error bars are the data, while the error band corresponds to the Monte Carlo predicted shape with systematic uncertainties. There is fairly good agreement between the data and Monte Carlo, except in the region near $\cos\theta = 1$, where the data is suppressed relative to the Monte Carlo prediction. This suppression may or may not be related to the suppression observed in the CCQE sample, and it remains, at present, an interesting mystery.
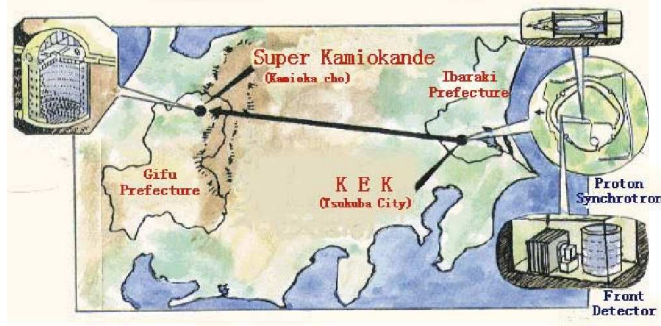
FIGURE 11. A schematic drawing of the K2K experiment, consisting of the KEK neutrino beam, the water Cherenkov near detector, the SCIBAR near detector, and the Super-Kamiokande far detector.

The MiniBooNE collaboration plans to complete its data collection in neutrino mode (corresponding to "positive" horn polarity) and switch to antineutrino running (corresponding to "negative" horn polarity) in January, 2006. Later in 2006, the collaboration will complete the "blind" oscillation analysis, present results, and publish a number of cross section measurements. If MiniBooNE confirms the LSND oscillation signal, then, together with solar and atmospheric oscillation data, it will imply Physics Beyond the Standard Model. Follow-on experiments (e.g. at Fermilab and at the SNS) will then be required to understand the nature of the "new" physics and its full implications.

K2K

The K2K experiment, as shown in Fig. 11, makes use of the KEK neutrino beam and consists of a 1-kton water Cherenkov near detector, a 15-ton plastic-scintillator near detector (SCIBAR), and the 50-kton Super-Kamiokande far detector. K2K has already confirmed the atmospheric neutrino oscillation signal [10] and has recently begun presenting cross section results based on the SCIBAR detector. Most interestingly, SCIBAR observes no evidence for coherent CCpi+ scattering, $\nu_\mu\ ^{12}C \rightarrow \mu^- \pi^+\ ^{12}C$. By fitting the Q^2 distribution of CCpi+ candidate events, as shown in Fig. 12, K2K measures the coherent CCpi+ fraction of all charged-current events to be $0.04 \pm 0.29^{+0.32}_{-0.35}\%$, corresponding to a 90% C.L. limit of $< 0.60\%$ [11]. The K2K coherent CCpi+ measurement is significantly lower than the theoretical prediction of Rein and Sehgal, [15] and this suppression of the coherent CCpi+ cross section may help explain the suppression of low-Q^2 CCpi+ events in MiniBooNE.

CONCLUSION

Neutrino physics has been spectacularly successful in recent years, culminating with the discovery of neutrino oscillations and neutrino mass. Nevertheless, this may be just the "Tip of the Iceberg"! The ongoing MiniBooNE and MINOS experiments at Fermilab will make definitive tests of the LSND result and measurements of atmospheric
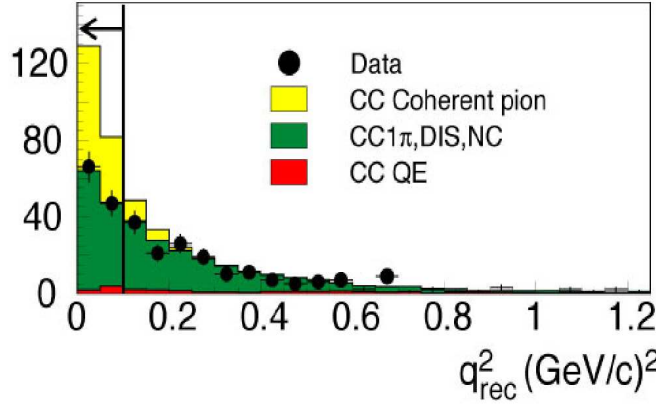
FIGURE 12. The K2K Q^2 distribution for CCpi+ candidate events. The coherent CCpi+ fraction of all charged-current events is < 0.60% at 90% C.L.

oscillations. For the future, exciting new neutrino experiments are planned in the areas of tritium β decay, neutrinoless double β decay, reactor θ_{13}, accelerator θ_{13}, solar neutrinos, large Δm^2, and neutrino cross sections. [9]

ACKNOWLEDGMENTS

REFERENCES

1. A. Aguilar et al., *Phys. Rev. D*, **64**, 112007 (2001).
2. Michel Sorel, Janet M. Conrad, Michael Shaevitz, *Phys. Rev. D*, **70**, 073004 (2004).
3. David B. Kaplan, Ann E. Nelson, Neal Weiner, *Phys. Rev. Lett.*, **93**, 091801 (2004); Rob Fardon, Ann E. Nelson, Neal Weiner, *JCAP*, **0410**, 005 (2004); Pham Quang Hung, Heinrich Pas, *Mod. Phys. Lett. A*, **20**, 1209–1216 (2005); P.Q. Hung, hep-ph/0010126; G. J. Stephenson, Jr. T. Goldman, B. H. J. McKellar, *Int. J. Mod. Phys. A*, **13**, 2765 (1998).
4. V. Barger, D. Marfatia, K. Whisnant, *Phys. Lett. B*, **576**, 303–308 (2003); Gabriela Barenboim and Joseph D. Lykken, *Phys. Lett. B*, **554**, 73–80 (2003); G. Barenboim, L. Borissov, Joseph D. Lykken, *Phys. Lett. B*, **534**, 106–113 (2002); G. Barenboim, L. Borissov, Joseph D. Lykken, A. Yu Smirnov, *JHEP*, **0210**, 001 (2002).
5. Gabriela Barenboim and Nick E. Mavromatos, *Phys. Rev. D*, **70**, 093015 (2004); Gabriela Barenboim and Nick E. Mavromatos, *JHEP*, **0501**, 034 (2005).
6. V. A. Kostelecky and M. Mewes, *Phys. Rev. D*, **70**, 076002 (2004).
7. Heinrich Pas, Sandip Pakvasa, Thomas J. Weiler, to appear in *Phys. Rev. D*.
8. Sergio Palomares-Ruiz, Silvia Pascoli, Thomas Schwetz, *JHEP*, **0509**, 048 (2005).
9. Talks from the PANIC05 Neutrino Satellite Meeting, which discussed future neutrino experiments, can be found at http://panic05.lanl.gov/neutrino/neutrino.html.
10. K2K collaboration: E. Aliu et al., *Phys. Rev. Lett.*, **94**, 081802 (2005).
11. K2K collaboration: M. Hasegawa, et al., hep-ex/0506008.
12. I. Chemakin et al., *Phys. Rev. C*, **65**, 024904 (2002).
13. HARP collaboration, hep-ex/0510039, accepted for publication in *Nucl. Phys. B*.
14. D. Casper, *Nucl. Phys. Proc. Suppl.* **112**, 161 (2002).
15. D. Rein and L. M. Sehgal, *Nucl. Phys. B* **223**, 29 (1983).